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6. AUTHORS W. Vincent Liu				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
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13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT We explored ultracold gases with seven projects during grant support. The supported research has resulted in 18 published articles, two of which are in Nature Physics, and 25 invited talks by the PI and postdocs. One of notable successes is the project of optical lattice p-orbital bands, which has gained considerable attention in recent years. Orbital physics of cold atoms is an emerging new topic in which, unlike most other topics, the theoretical development was earlier than the experiments. PI's contribution includes having published one of the earliest three					
15. SUBJECT TERMS physics, interacting atoms, ultra-low temperature quantum physics					
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a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 412-624-9023

Report Title

Final report for the proposal of exotic phases of ultracold atoms

ABSTRACT

We explored ultracold gases with seven projects during grant support. The supported research has resulted in 18 published articles, two of which are in Nature Physics, and 25 invited talks by the PI and postdocs. One of notable successes is the project of optical lattice p-orbital bands, which has gained considerable attention in recent years. Orbital physics of cold atoms is an emerging new topic in which, unlike most other topics, the theoretical development was earlier than the experiments. PI's contribution includes having published one of the earliest three theoretical papers that started this new field. Throughout the support period, the PI's team remains a leading research group of this subject, as evidenced by, for example, the invited talks in the APS March meeting and KITP Santa Barbara conference. The supported research, while being theoretical, have had a direct impact on experimental directions. For instance, the theoretical research of p-orbital bosons on the optical lattices has led to the new experimental setups of such systems by the world's most eminent experimental groups such as I. Bloch and A. Hemmerich. Our prediction of a new quantum phase - finite-momentum $p_x + ip_y$ Bose-Einstein condensate - was examined and partially confirmed by experiments [I. Bloch et al, Phys. Rev. Lett, 2007; A. Hemmerich et al, Nature Physics, 2011].

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
2011/11/20 1: 20	Kai Sun, Erhai Zhao, W. Vincent Liu. Topological Phases of Dipolar Particles in Elongated Wannier Orbitals, Physical Review Letters, (04 2010): 0. doi: 10.1103/PhysRevLett.104.165303
2011/11/20 1: 19	Xiaopeng Li, W. V. Liu, Chungwei Lin. Bose-Einstein supersolid phase for a type of momentum-dependent interaction, Physical Review A, (02 2011): 0. doi: 10.1103/PhysRevA.83.021602
2011/11/20 1: 18	Zixu Zhang, W. Vincent Liu. Finite-temperature damping of collective modes of a BCS-BEC crossover superfluid, Physical Review A, (02 2011): 0. doi: 10.1103/PhysRevA.83.023617
2011/11/20 1: 17	Kai Sun, W. Vincent Liu, Andreas Hemmerich, S. Das Sarma. Topological semimetal in aferrionic optical lattice, Nature Physics, (11 2011): 0. doi: 10.1038/nphys2134
2011/11/20 1: 14	Zixu Zhang, Hsiang-Hsuan Hung, Chiu Ho, Erhai Zhao, W. Vincent Liu. Modulated pair condensate of p-orbital ultracold fermions, Physical Review A, (09 2010): 0. doi: 10.1103/PhysRevA.82.033610
2011/11/20 1: 13	Erhai Zhao, W. Vincent Liu. Orbital Order in Mott Insulators of Spinless p-Band Fermions, Physical Review Letters, (04 2008): 0. doi: 10.1103/PhysRevLett.100.160403
2011/11/20 1: 10	Xiaopeng Li, Erhai Zhao, W. Liu. Effective action approach to the p-band Mott insulator and superfluid transition, Physical Review A, (06 2011): 0. doi: 10.1103/PhysRevA.83.063626
2011/11/20 1: 9	Vladimir Stojanovi?, Congjun Wu, W. Liu, S. Das Sarma. Incommensurate Superfluidity of Bosons in a Double-Well Optical Lattice, Physical Review Letters, (09 2008): 0. doi: 10.1103/PhysRevLett.101.125301
2011/11/20 1: 8	Erhai Zhao, W. Vincent Liu. An Effective Field Theory for One-dimensional Polarized Fermi Gases, J. Low Temp. Phys., (05 2010): 0. doi:
2011/11/20 1: 7	Chungwei Lin, Xiaopeng Li, W. Liu. $U(1) \times U(1)$ to Z_2 Kosterlitz-Thouless transition of the Larkin-Ovchinnikov phase in an anisotropic two-dimensional system, Physical Review B, (03 2011): 0. doi: 10.1103/PhysRevB.83.092501
2011/11/20 1: 6	Vladimir M. Stojanovic, W. Vincent Liu, Yong Baek Kim. Unconventional interaction between vortices in a polarized Fermi gas, Annals of Physics, (04 2008): 0. doi: 10.1016/j.aop.2007.09.009
2010/03/25 1: 5	E. Zhao, W. Liu. Theory of quasi-one-dimensional imbalanced Fermi gases, Physical Review A, (03 2010): . doi:
2010/03/25 1: 2	W. Liu. Liquid crystal phases of ultracold dipolar fermions on a lattice, Physical Review B, (01 2010): . doi:
2010/03/25 1: 1	E. Zhao, X. Guan, W. Liu, M. Batchelor, M. Oshikawa. Analytic Thermodynamics and Thermometry of Gaudin-Yang Fermi Gases, Physical Review Letters, (10 2009): . doi:

TOTAL: 14

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
2011/11/20 1: 12	W. Vincent Liu, Maciej Lewenstein. Orbital dance, Nature Physics, (02 2011): 0. doi:

TOTAL: 1

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

<u>Received</u>	<u>Paper</u>
2011/11/20 16	Zixu Zhang, Xiaopeng Li, W. Vincent Liu. Orbital Liquid Crystal Phases of Cold Fermions in Optical Lattices, arXiv:1105.3387 (05 2011)
2011/11/20 15	Philipp Hauke, Erhai Zhao, Kritika Goyal, Ivan H. Deutsch, W. Vincent Liu, Maciej Lewenstein. Time-reversal symmetry breaking of fermions in the p-band of an optical lattice, arXiv:1103.5964 (03 2011)
2011/11/20 11	Xiaopeng Li, Zixu Zhang, W. Vincent Liu. Time reversal symmetry breaking of s -orbital bosons in a one-dimensional optical lattice, arXiv:1110.3364 (10 2011)
2010/03/25 4	Z. Zhang, H. Hung, C. Ho, E. Zhao, W. Liu. Center-of-mass p-wave fermionic superfluidity, (11 2009)
2010/03/25 3	K. Sun, E. Zhao, W. Liu. Topological phases of dipolar particles in elongated Wannier orbitals, (08 2009)

TOTAL: 5

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

* General Member (on sabbatical leave with pay from KITP), Kavli Institute for Theoretical Physics, University of California, Santa Barbara, 8/23–9/05/2010 & 12/18/2010– 6/10/2011

*Lead coordinator, KITP Conference, “Frontiers of Ultracold Atoms and Molecules,” Kavli Institute for Theoretical Physics, UCSB, Santa Barbara, Oct 11–15, 2010

*Lead coordinator (primary contact), KITP Program, “Beyond Standard Optical Lattices,” Kavli Institute for Theoretical Physics, UCSB, Santa Barbara, September 13–December 10, 2010.

* Co-Organizer (with P. Zoller, C. P. Sun, F. Zhou, et al), KITPC Program, “CondensedMatter Physics of Cold Atoms,” Kavli Institute for Theoretical Physics China (KITPC), Chinese Academy of Sciences, Beijing, China, Sep 21–Nov 6, 2009.

* 2007 “Outstanding Young Researcher Award”, Overseas Chinese Physics Association
<http://www.ocpaweb.org/new/oyraaward/oyraaward.html>

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
Vladimir Stojanovic	1.00	
Zixu Zhang	1.00	
Xiaopeng Li	0.50	
FTE Equivalent:	2.50	
Total Number:	3	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Erhai Zhao	0.20
Chungwei Liu	0.20
FTE Equivalent:	0.40
Total Number:	2

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
W. Vincent Liu	0.17	
FTE Equivalent:	0.17	
Total Number:	1	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PhDs

NAME

Vladimir Stojanovic

Total Number:

1

Names of other research staff

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment.

Technology Transfer

Final Report
Exotic phases of ultracold atoms
ARO W911NF-07-1-0293
May 2007—August 31, 2011

Prepared by
W. Vincent Liu
Organization: University of Pittsburgh
November 18, 2011

Abstract

We explored ultracold gases with seven projects during grant support. The supported research has resulted in 18 published articles, two of which are in *Nature Physics*, and 25 invited talks by the PI and postdocs. One of notable successes is the project of optical lattice p -orbital bands, which has gained considerable attention in recent years. Orbital physics of cold atoms is an emerging new topic in which, unlike most other topics, the theoretical development was earlier than the experiments. PI's contribution includes having published one of the earliest three theoretical papers that started this new field. Throughout the support period, the PI's team remains a leading research group of this subject, as evidenced by, for example, the invited talks in the APS March meeting and KITP Santa Barbara conference.

The supported research, while being theoretical, have had a direct impact on experimental directions. For instance, the theoretical research of p -orbital bosons on the optical lattices has led to the new experimental setups of such systems by the world's most eminent experimental groups such as I. Bloch and A. Hemmerich. Our prediction of a new quantum phase - finite-momentum $p_x + ip_y$ Bose-Einstein condensate - was examined and partially confirmed by experiments [I. Bloch *et al*, Phys. Rev. Lett, 2007; A. Hemmerich *et al*, Nature Physics, 2011].

1 Introduction

This is the final report for the proposal titled “Exotic phases of ultracold atoms.” It is organized as follows. Section 2 summarizes the technical aspects of the scientific progress and accomplishment. Section 3 reports the impact of the supported research viewed from scholarly activities. Section 4 reports collaborative research activities. Section 5 lists papers published with the support for this proposal.

2 Accomplished Research Projects

In this period, we carried out research with the following 7 projects, summarized below.

1. *Spin imbalance, exotic breached pairing, and novel superfluidity in 3D*

- (a) Systematically studied unconventional vortex properties of a (gapless) imbalanced fermionic superfluid (BP1 phase). (Our work [1])
- (b) Found that the topological transition of the Larkin-Ovchinnikov phase in an anisotropic two-dimensional system is not described by the U(1) Kosterlitz-Thouless physics typically characteristic of the 2D superfluid, but by the new universality class of $U(1) \times U(1) / Z_2$ due to the presence of fractional topological defects such as half vortex and half edge dislocation. (Our work [2])

2. *One-dimensional spin-imbalanced Fermi gases*

- (a) Developed effective field theory of quasi-1D atomic gases based on Bethe Ansatz and Conformal Field Theory. Our effective Lagrangian is generalized to higher dimensions (beyond 1D), providing a Bethe Ansatz-based field theory description with controlled approximation for strong interaction. Such a theory was not previously available. The result is published in [3, 4].
- (b) Made a breakthrough in exact solution for strongly interacting Fermi gases in one dimension. That is, we reduced the infinite set of coupled integral equations, known as the thermodynamic Bethe ansatz solution, to a set of four algebraic equations in the experimental regime [Rice/Hulet group] - strong interaction and relatively low temperature. (Our work [5])

3. *Novel phases of p-orbital bands of optical lattices - bosons*

- (a) Explored novel orbital order and superfluidity of p-band bosons with double-well optical lattice configurations (our work [6]). This 2008 work is several years earlier than the pioneer double-well optical lattice experiment of the Hamburg/Hemmerich group which first reported a long-lived p-band Bose-Einstein condensate [G. Wirth, M. Ölschläger, and A. Hemmerich, Nature Physics 7, 147 (2011)].
- (b) Established the phase diagram of p-band bosons with both Mott and superfluid phases. Found two classes of orbital Neel ordered Mott phases, distinguished by whether time-reversal symmetry is broken or not. (Our work [7])
- (c) A novel feature of the p-band bosons we and other groups have independently found is the time reversal symmetry breaking in both superfluid and Mott insulator phases. Here we proposed an optical lattice system that can unambiguously check this prediction. (Our work [8])
- (d) Wrote a perspective in Nature Physics on the emergent new topic - orbital physics of optical lattices. (Our work [9])

4. *Novel phases of p-orbital bands of optical lattices - fermions*

- (a) Published the first theoretical proposal of how to realize orbital-only strongly correlated models with ultracold fermions. It shows Mott insulator with orbital correlations, quantum

120° model, and novel orbital orderings such as orbital antiferromagnetic state, 15° (30°) orbital-bond order on Kagomé (honeycomb) lattice, etc. (Our work [10])

- (b) First study of imbalanced Fermi gases in a new regime: spin imbalance leads to band imbalance in an optical lattice. We found a new s - p hetero-orbital paired superfluid where the bosonic pair wavefunction is p -wave (so it has nodes) and yet it is a stable ground state. This result is interesting in view of Feynman's no node theorem. (Our work [11])
 - (c) Extended the study of our early work [10] to the case of three degenerate orbital states and explicit time-reversal symmetry breaking p -wave interactions in a 3D optical lattice. (Our work [12])
 - (d) Predicted orbital liquid crystal phases of cold fermions in optical lattices. (Our work [13])
 - (e) Discovered a topological semimetal phase and its quantum transition towards a topological insulator whose experimental signature includes chiral gap-less domain-wall modes, reminiscent of quantum Hall edge states. This work has been accepted for publication in Nature Physics as a letter. (Our work [14])
5. *Damping of collective modes in BEC-BCS crossover superfluids.* We proposed a new mechanism to explain the puzzling damping of collective excitations, which was recently observed in the experiments of strongly interacting Fermi gases in the BCS-BEC crossover regime. An effective field theory framework was used to deal with strong interaction. (Our work [15])
6. *Dipolar quantum gases and topological phases*
- (a) Found that dipolar particles in elongated Wannier orbitals of a Kagome optical lattice can realize the triangular quantum dimer model in condensed matter physics, which is known from past exact numerics to have fractional excitations. This is a model claimed to be a potential candidate to explain the exotic spin liquid physics, widely pursued in strongly correlated physics such as high temperature superconductors. Our study provides a first possible, direct realization scheme with dipolar cold quantum particles (atoms or molecules). (Our work [16])
 - (b) Explored quantum liquid crystal phases of dipolar fermions on two-dimensional lattices. (Our work [17])
7. *Bose-Einstein supersolid.* Found Bose-Einstein supersolid phase for a novel class of momentum dependent (non-local) interaction between bosons. This finding is consistent with a recent independent exact numerical study by Cinti, Zoller et al [arXiv:1005.2403]. (Our work [18])

3 Research Impact

(a) Prediction vs. Experimental Observation

An exciting experimental development appeared lately (June 2010), which is about the p -band bosons that we are among the first authors having studied.

Hemmerich's group in Hamburg reported "the first observation of a superfluid in the P -band of a bipartite optical square lattice with S -orbitals and P -orbitals arranged in a checkerboard pattern" [G. Wirth, M. Ölschläger, A. Hemmerich, arXiv:1006.0509v3, Nat. Phys. **7**, 147 (2011) ; their Ref. [9] and [16] are our work]. This is the topic which the PI and his collaborators are among the first to put forward. Other early theory groups include S. Girvin and A. Isacson; A. Kuklov; etc. We predicted the finite momentum BEC of p -band bosons and $p_x + ip_y$ complex orbital order for a simple cubic or square lattice in [W. V. Liu and C. Wu, PRA 2006]. Hemmerich et al reported the observation of such phases, albeit in a different optical lattice configuration.

(b) Nature Physics articles

The PI was among the early three theoretical papers (published 2005-2006) that started the field of p -orbital physics with optical lattices. Our group has since continued to be active at the forefront of this emergent new topic. As a result, two Nature Physics articles from this group are published (or accepted): [9] and [14].

(c) Invited Talks

INVITED TALKS BY PI

<i>14 Oct 2011</i>	University of New Brunswick, Department of Physics, Colloquium: "Ultracold atoms tuned to new many-body regimes", Fredericton, Canada
<i>27 Sep 2011</i>	Penn State University, Department of Physics, CAM Seminar: "Novel p -band superfluid and insulator phases in optical lattices," University Park, PA.
<i>18-22 July 2011</i>	Advanced Workshop on "Non-standard superfluids and insulators", ICTP, Trieste, Italy, invited talk: " p -band superfluid and insulator phases in optical lattices"
<i>13 July 2011</i>	Universität Hamburg, Institute of Laser Physics, Colloquium of the Center for Optical Quantum Technologies: "Ultracold atoms in the unprecedented regimes of condensed matter"
<i>17 Feb 2011</i>	Brown University, Department of Physics, Condensed Matter Seminar: "Ultracold spin-imbalanced Fermi gases in low dimensions"
<i>3-8 Jan 2011</i>	International Conference "Frontiers of Condensed Matter Physics", Stockholm, Sweden, January 3-8, 2011, invited talk: "Ultracold spin-imbalanced Fermi gases in low dimensions"
<i>14 Dec 2010</i>	Boston College, Department of Physics, Condensed Matter Seminar: "Beyond the s -orbital band of optical lattices: from finite-momentum $p_x + ip_y$ Bose-Einstein condensation to topological semi-Fermi liquids"

- 27 July 2010 Department of Physics, Ludwig-Maximilians-Universität (LMU), Munich, Germany. Quantum Optics Group (of Professor I. Bloch) Seminar: "p-orbital ultracold particles and Bose-Einstein crystal"
- 22 July 2010 NORDITA Workshop "Quantum solids, liquids, and gases," Stockholm, Sweden, 19 July —27 Aug, 2010. Invited talk: "p-orbital ultracold particles and Bose-Einstein crystal."
- 6 July 2010 CAS 4th International Symposium on Cold Atom Physics, July 5-8, 2010, Zhoushan Islands, Zhejiang, China. Sponsored by Center for Cold Atom Physics (Shanghai), Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences. More than 260 participants. Invited talk: "Novel p-orbital quantum phases in cold atom optical lattices"
- 25 Feb 2010 Department of Physics, Univ of Maryland, College Park. CNAM Condensed Matter Colloquium: "Exotic superfluidity of spin imbalanced fermions: from three to one dimension"
- 17 Nov 2009 Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Innsbruck, Austria. Quantum Optics Seminar: "Orbital phases in optical lattices."
- 11-13 Nov 2009 Workshop on "Ab-initio Modeling of Cold Gases," CECAM/ETH, Zurich, Switzerland, November 11-13, 2009. Invited talk: "Cold atoms and molecules in elongated Wannier orbitals."
- 8 Sep 2009 Conference: Bose-Einstein Condensation 2009, Frontiers in Quantum Gases, Sant Feliu de Guixols (Costa Brava), Spain, 05-11 September 2009. Invited short talk: "Analytic thermodynamics and thermometry of 1D imbalanced Fermi gases at strong interaction."
- 20 Mar 2009 APS March Meeting, Pittsburgh, PA, March 16-20, 2009. Invited talk in the invited session, "Novel orbital quantum phases in cold atom optical lattices". Talk title: "Non-zero momentum Bose-Einstein condensation of orbital atoms."
- 8 Jan 2009 PQE 2009: 39th Winter Colloquium on the Physics of Quantum Electronics, Snowbird, Utah, January 4-8, 2009. Invited talk in the "Optical Lattice" Session: "Crystalline superfluidity of cold atoms in lattice p-bands."
- 7 Nov 2008 Department of Physics, Purdue University. Condensed Matter and Biological Physics Seminar: "Crystalline superfluidity of ultracold Bose and Fermi gases."
- 19 Aug 2008 Aspen Center for Physics. Summer Workshop, "Frontiers in Strongly Correlated Systems," Seminar: "Orbital physics of optical lattices."
- 22 Aug 2007 National Institute of Standards and Technology (NIST), Gaithersburg. Quantum Information/BEC (QIBEC) Seminar: "Orbital order in optical lattices".

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|--------------|---|
| 10 July 2007 | Henri Poincare Institute, Paris, France, Quantum Gases Program Seminar: "Some unconventional phases of cold atomic matter with or without an optical lattice". |
| 7 June 2007 | APS DAMOP/DAMP (38th Annual Meeting of APS Division of AMO), 5-9 June 2007, Calgary, Canada. Invited speaker in the "Optical Lattices" session: "Orbital phases of cold atoms in the lattice p-orbital band" |
| 8 May 2007 | KITP, U. California Santa Barbara. "Strongly Correlated Phases in Condensed Matter and Degenerate Atomic Systems" Program Seminar: "Exploring New Phases of Cold Atomic Matter with or without an Optical Lattice". |

INVITED TALKS BY POSTDOCS AND STUDENTS

1. Erhai Zhao (postdoc), "Ultracold Fermi Gases in One and Quasi-one Dimension," KITP Conference: Frontiers of Ultracold Atoms and Molecules, Kavli Institute for Theoretical Physics, UC Santa Barbara, Oct 11-15, 2010
2. Erhai Zhao (postdoc), "One-dimensional Fermi gas with spin imbalance", Center for Advanced Studies, Tsinghua University, China, Oct. 2009
3. Erhai Zhao (postdoc), "Building a crystalline superfluid one tube at a time", Kavli Institute of Theoretical Physics China, Oct. 2009
4. Erhai Zhao (postdoc), "Orbital physics in the ultracold", Kavli Institute of Theoretical Physics China, Oct. 2009
5. Erhai Zhao (postdoc), "Theory of quasi-one dimensional imbalanced Fermi gases", International Symposium on Quantum Fluids and Solids (QFS 2009), Northwestern University, Aug. 2009

(d) Contributed Talks and Conference Activities

1. C. Lin, " $U(1) \times U(1)$ to Z_2 Kosterlitz-Thouless transition of the Larkin-Ovchinnikov phase in an anisotropic two-dimensional system", contributed talk in the session on "Quantum Fluids and Solids II", APS March Meeting, Dallas, TX, March 21-25, 2011.
2. Zixu Zhang, " $(2k_F, 2k_F)$ density-wave orders of interacting p-orbital fermions in square optical lattice", APS March Meeting, Dallas, Texas, March 21-25, 2011.
3. X. Li, " $U(1) \times Z_2$ transition from the Mott insulator to $p_x + ip_y$ Bose-Einstein superfluid phase" in the session on "Exotic Quantum Phases in Optical Lattices: FFLO, P-band Physics, and Beyond", APS March Meeting, Dallas, Texas, March 21-25, 2011.

4. X. Li, "The Bose-Einstein supersolid phase with momentum dependent interaction" in the session on "Ultracold Dipolar Gases" in the program "Beyond standard optical lattice" Kavli Institute for Theoretical Physics, University of California, Santa Barbara (22 Oct 2010).
5. Chungwei Lin (postdoc), "Liquid crystal phases of ultracold dipolar fermions on a lattice," contributed talk in the session on "Molecular and Dipolar Quantum Gases," APS March Meeting, Portland, Oregon, March 15-19, 2010.
6. Zixu Zhang (student), "Center-of-mass p -wave fermionic superfluidity," APS March Meeting, Portland, OR, March 15-19, 2010.
7. Xiaopeng Li (student), "Bose-Einstein crystal phase of cold gases with momentum dependent interaction," contributed talk in the session on "Molecular and Dipolar Quantum Gases," APS March Meeting, Portland, OR, March 15, 2010.
8. E. Zhao (post doc), "Effective theory for weakly coupled one-dimensional imbalanced Fermi gas", oral presentation, APS March meeting, Pittsburgh, PA, March 19, 2009.
9. Zixu Zhang (grad student), American Physical Society(APS) March Meeting, March 16-20, 2009, Pittsburgh, PA. (Attended)
10. PI, Paris Program on "Quantum Gases", Centre Emile Borel, Institut Henri Poincaré, April 23- July 20, 2007, Paris, France, to participate June 24 —July 20. (invited)
11. PI, KITP (Santa Barbara) Program on "Strongly Correlated Phases in Condensed Matter and Degenerate Atomic Systems", participated Apr 30–May 25, 2007. (invited)
12. Erhai Zhao, "Orbital ordering in an atomic Mott insulator of p -band fermions", contributed talk at the APS March Meeting, New Orleans, March 13, 2008. (23 Jan 2003).
13. V. M. Stojanović, "Incommensurate superfluidity of bosons in the optical lattice of double-well potentials", APS March Meeting, New Orleans (March 12, 2008).
14. V. M. Stojanović, KITP (Santa Barbara) Program on "Strongly Correlated Phases in Condensed Matter and Degenerate Atomic Systems", participated Apr 30–May 25, 2007. (Graduate affiliate)

(e) Recognitions

PI received the following recognitions during the reporting period:

1. General Member (on sabbatical leave with pay from KITP), Kavli Institute for Theoretical Physics (KITP), University of California, Santa Barbara, 8/23–9/05/2010 & 12/18/2010–6/10/2011

2. Lead coordinator, KITP Conference, “Frontiers of Ultracold Atoms and Molecules,” Kavli Institute for Theoretical Physics, UCSB, Santa Barbara, Oct 11–15, 2010,
http://www.kitp.ucsb.edu/activities/dbdetails?acro=BOPTILATT_C10
3. Lead coordinator (primary contact), KITP Program, “Beyond Standard Optical Lattices,” Kavli Institute for Theoretical Physics, UCSB, Santa Barbara, September 13–December 10, 2010.
<http://www.kitp.ucsb.edu/activities/dbdetails?acro=BOPTILATT10>
4. Co-Organizer (with P. Zoller, C. P. Sun, F. Zhou, et al), KITPC Program, “Condensed Matter Physics of Cold Atoms,” Kavli Institute for Theoretical Physics China (KITPC), Chinese Academy of Sciences, Beijing, China, Sep 21–Nov 6, 2009.
<http://www.kitpc.ac.cn/program.jsp?id=PC20090921>
5. 2007 “Outstanding Young Researcher Award”, Overseas Chinese Physics Association
<http://www.ocpaweb.org/new/oyraaward/oyraaward.html>
6. Awarded tenure by the University of Pittsburgh. Promoted to the rank of Associated Professor, effective Sep 1, 2009.
7. Visiting Scientist, Centre Emile Borel, Institut Henri Poincaré, Paris, France (with daily financial support), 6/24–7/20/07.

(f) Service and Contribution to the Scientific Community

1. co-organizer, 6-week KITPC Program on “Condensed matter physics of cold atoms,” Kavli Institute for Theoretical Physics China at the Chinese Academy of Sciences, Beijing, China, Sep 21–Nov 6, 2009. Web: <http://www.kitpc.ac.cn/program.jsp?id=PC20090921>
International coordinator: W. Vincent Liu, Chang-Pu Sun, Fei Zhou, Peter Zoller
Local coordinators: Wu-ming Liu, Biao Wu, Su Yi, Yue Yu
2. Organizer (primary contact), KITP Santa Barbara 3-month Program: “Beyond Standard Optical Lattices,” Kavli Institute for Theoretical Physics, UCSB, Santa Barbara, September 13, 2010– December 10, 2010.
Web: <http://www.kitp.ucsb.edu/activities/dbdetails?acro=BOPTILATT10>
Coordinators: Ehud Altman, Maciej Lewenstein, W. Vincent Liu
Scientific Advisors: Immanuel Bloch, Sankar Das Sarma, Mikhail Lukin, William Phillips
3. Lead organizer, KITP Santa Barbara Conference: “Frontiers of Ultracold Atoms and Molecules,” Oct 11-15, 2010. This conference is associated with the 2010 KITP Program (above).
Web: <http://www.kitp.ucsb.edu/activities/dbdetails?acro=boptilatt-c10>
Conference organizing committee: Ofir Alon, Immanuel Bloch, W. Vincent Liu, William Phillips

4 Collaborative Research

(a) People in PI's group

During the reporting period, PI's research group had three students: Vladimir Stojanovic, Zixu Zhang and Xiaopeng Li; and two postdoc associates: Erhai Zhao and Chungwei Lin.

Erhai Zhao (postdoc at Pittsburgh from Sep 2007–Aug 2009) has taken up a faculty position in the Department of Physics at George Mason University in Fairfax, VA.

Chungwei Lin started at Pittsburgh as a new postdoc in February, 2009. He received his PhD in 2008 from Columbia University, under supervision of Professor Andrew Millis (condensed matter theorist). Dr. Lin now is a postdoc associate at University of Texas at Austin.

(b) Collaborations

PI's group had collaborations during the reporting period with:

- M. T. Batchelor (Australian National University)
- S. Das Sarma (Univ of Maryland)
- X.-W. Guan (Australian National University)
- C. Ho (UC Berkeley; now at Vanderbilt University)
- H.-H. Hung (UCSD)
- Y. B. Kim (Univ of Toronto, Canada)
- J. Moore (UC Berkeley)
- M. Oshikawa (U of Tokyo)
- V. M. Stojanovic (Carnegie Mellon Univ)
- K. Sun (postdoc at Joint Quantum Institute, U of Maryland)
- C. Wu (UCSD)

(c) Supported Visitors and Participants

The following visitors were supported in part or full by the ARO grant during their extended visits:

- Dr. Kai Sun, Department of Physics, UIUC, Nov 10–12, 2008. Sun is a new PhD from UIUC. He gave a Department-wide condensed matter seminar and a lecture in PI's group.

- Prof. Han Pu, Department of Physics and Astronomy, Rice University, March 20–26, 2009. Prof. Pu gave a seminar and an informal talk. He is a world leader in quantum dipolar gases. For instance, he gave an invited talk and chaired another invited session on this subject in the 2009 APS March Meeting.
- Mr. Hsiang-Hsuan Hung, graduate student, Department of Physics, UCSD, March 20–24, 2009. He is a student with Prof. Congjun Wu in UCSD.
- Dr. Sabastian Huber, ETH, Zurich, Switzerland July 23–26, 2008. Huber is a new PhD from ETH Zurich. He gave two lectures during his extended visit to PI's group.

5 Publications supported by the grant

- [1] V. M. Stojanović, W. V. Liu, and Y. B. Kim, “Unconventional interaction between vortices in a polarized Fermi gas,” *Ann. Phys.* **323** (2008) 989.
- [2] C. Lin, X. Li, and W. V. Liu, “ $U(1) \times U(1)$ to Z_2 Kosterlitz-Thouless transition of the Larkin-Ovchinnikov phase in an anisotropic two-dimensional system,” *Phys. Rev. B* **83** (2011) 092501.
- [3] E. Zhao and W. V. Liu, “Theory of quasi-one dimensional imbalanced Fermi gases,” *Phys. Rev. A* **78** (2008) 063605.
- [4] E. Zhao and W. V. Liu, “An effective field theory for one-dimensional polarized fermi gases,” *J. Low Temp. Phys.* **158** (2010) 36.
- [5] E. Zhao, X.-W. Guan, W. V. Liu, M. T. Batchelor, and M. Oshikawa, “Analytic thermodynamics and thermometry of Gaudin-Yang Fermi gases,” *Phys. Rev. Lett.* **103** (2009) 140404.
- [6] V. M. Stojanović, C. Wu, W. V. Liu, and S. Das Sarma, “Incommensurate superfluidity of bosons in a double-well optical lattice,” *Phys. Rev. Lett.* **101** (2008) 125301.
- [7] X. Li, E. Zhao, and W. V. Liu, “Effective action approach to the p -band Mott insulator and superfluid transition,” *Phys. Rev. A* **83** (2011) 063626.
- [8] X. Li, Z. Zhang, and W. V. Liu, “Time reversal symmetry breaking of p -orbital bosons in a one-dimensional optical lattice.” arXiv:1110.3364.
- [9] M. Lewenstein and W. V. Liu, “Optical lattices: Orbital dance,” *Nature Physics* **7** (2011) 101.
- [10] E. Zhao and W. V. Liu, “Orbital order in Mott insulators of spinless p -band fermions,” *Phys. Rev. Lett.* **100** (2008) 160403.
- [11] Z. Zhang, H.-H. Hung, C. M. Ho, E. Zhao, and W. V. Liu, “Modulated pair condensate of p -orbital ultracold fermions,” *Phys. Rev. A* **82** (2010) 033610.
- [12] P. Hauke, E. Zhao, K. Goyal, I. H. Deutsch, W. V. Liu, and M. Lewenstein, “Time-reversal symmetry breaking of fermions in the p -band of an optical lattice.” arXiv:1103.5964.
- [13] Z. Zhang, X. Li, and W. V. Liu, “Orbital Liquid Crystal Phases of Cold Fermions in Optical Lattices.” arXiv:1105.3387.

- [14] K. Sun, W. V. Liu, A. H. Hemmerich, and S. Das Sarma, “Topological semimetal in a fermionic optical lattice.” arXiv:1011.4301 (initial version); final version accepted for publication in *Nature Physics*.
- [15] Z. Zhang and W. V. Liu, “Finite-temperature damping of collective modes of a BCS-BEC crossover superfluid,” *Phys. Rev. A* **83** (2011) 023617.
- [16] K. Sun, E. Zhao, and W. V. Liu, “Topological phases of dipolar particles in elongated Wannier orbitals,” *Phys. Rev. Lett.* **104** (2010) 165303.
- [17] C. Lin, E. Zhao, and W. V. Liu, “Liquid crystal phases of ultracold dipolar fermions on a lattice,” *Phys. Rev. B* **81** (2010) 045115. Erratum: *Phys. Rev. B* **83** 119901 (2011).
- [18] X. Li, W. V. Liu, and C. Lin, “Bose-Einstein supersolid phase for a type of momentum-dependent interaction,” *Phys. Rev. A* **83** (2011) 021602.